Calibrating LSST photometric redshifts with cross-correlations

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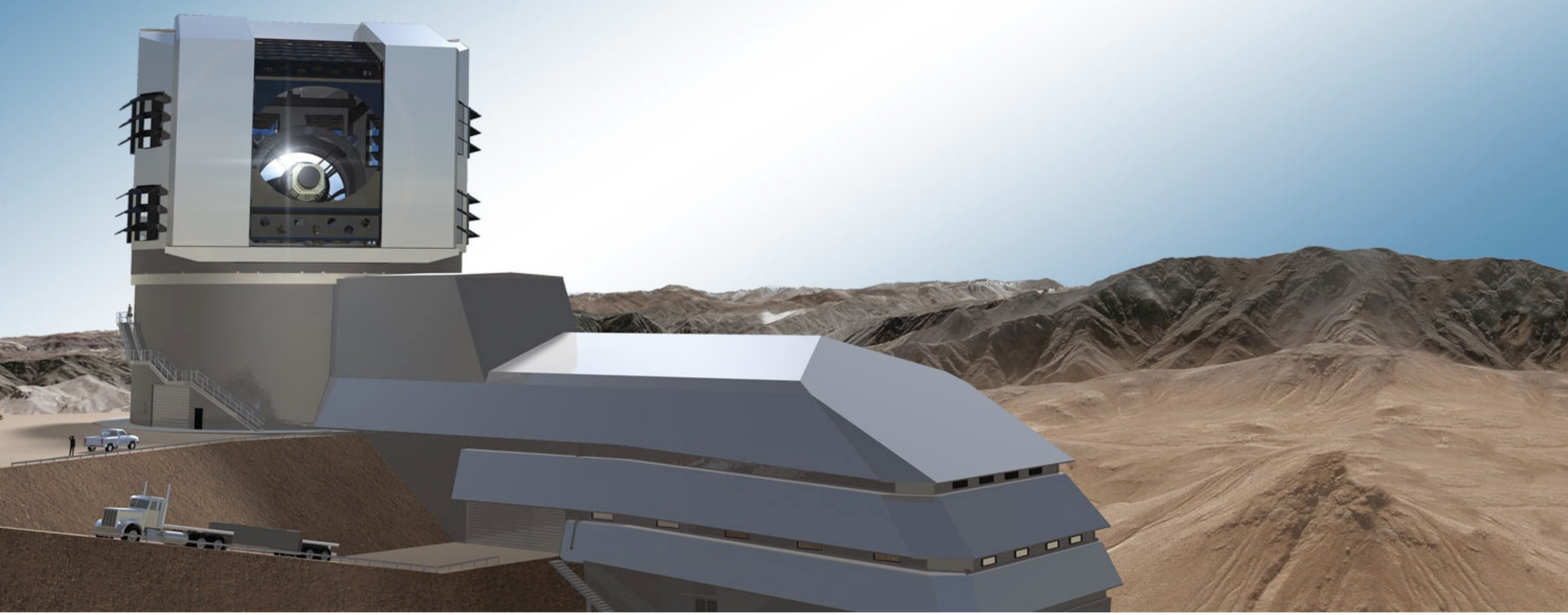
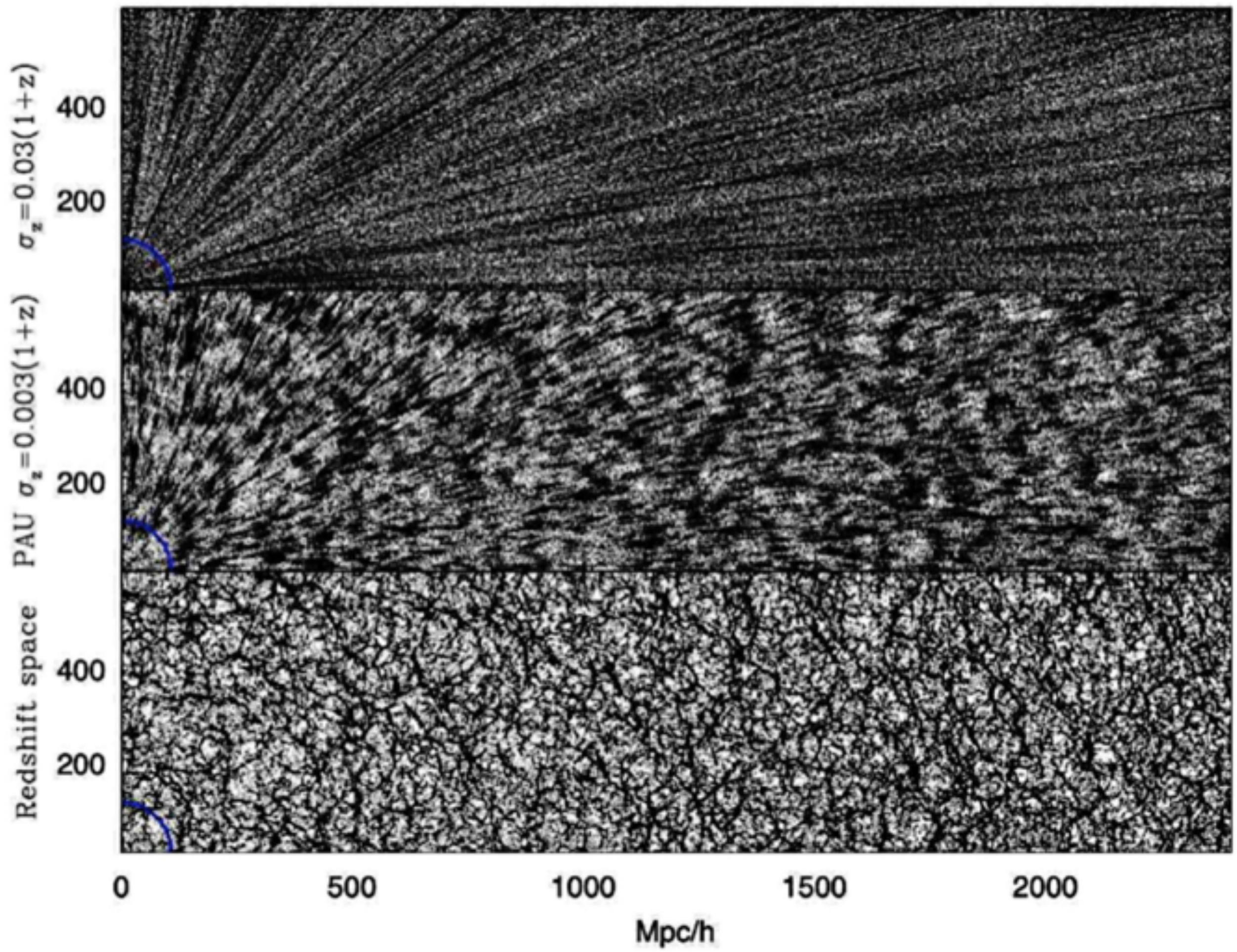


Two spectroscopic needs for photo-z work: training and calibration

- Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves DE constraints, esp. for BAO and clusters



Benitez et al. 2009

  - Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.

Two spectroscopic needs for photo-z work: training and calibration

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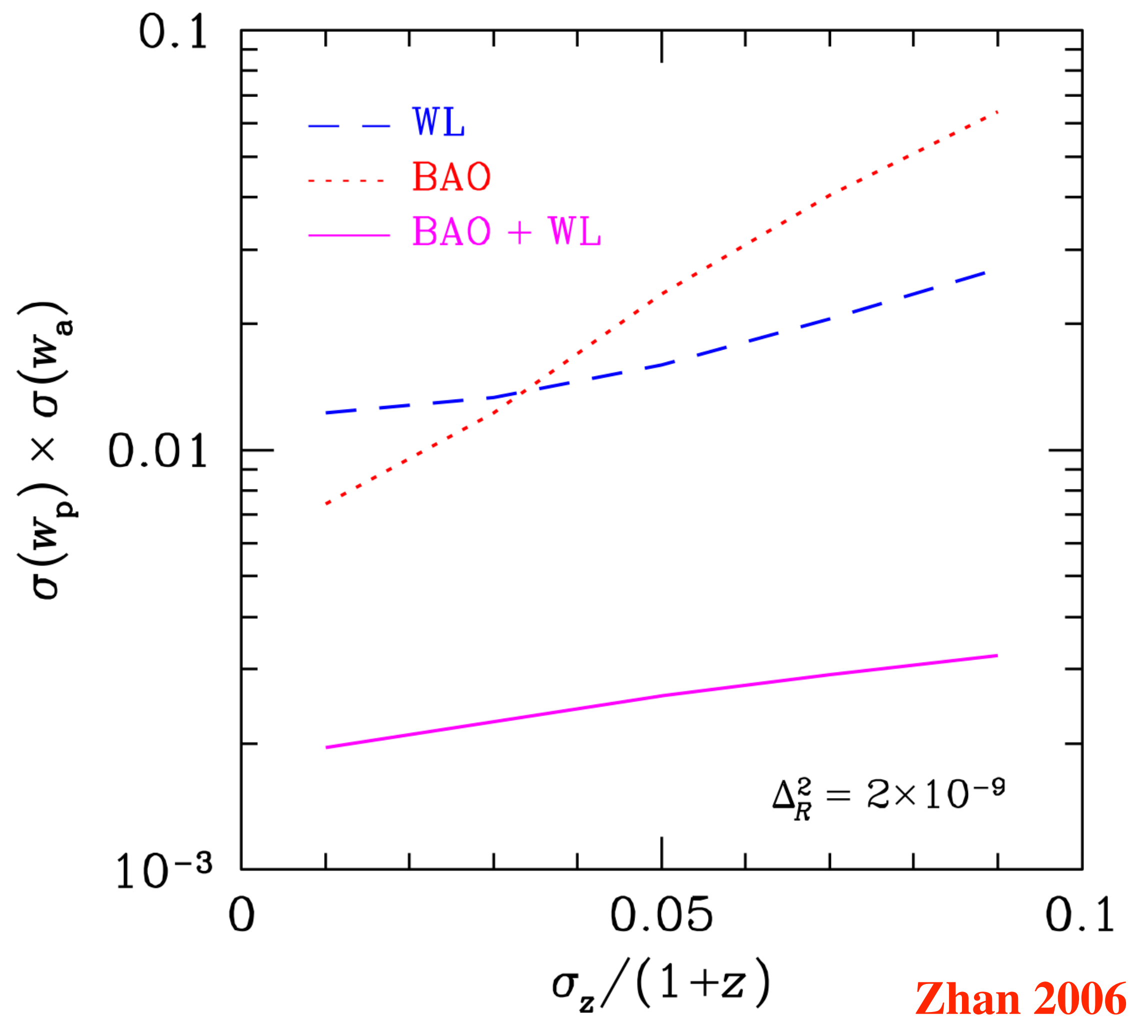
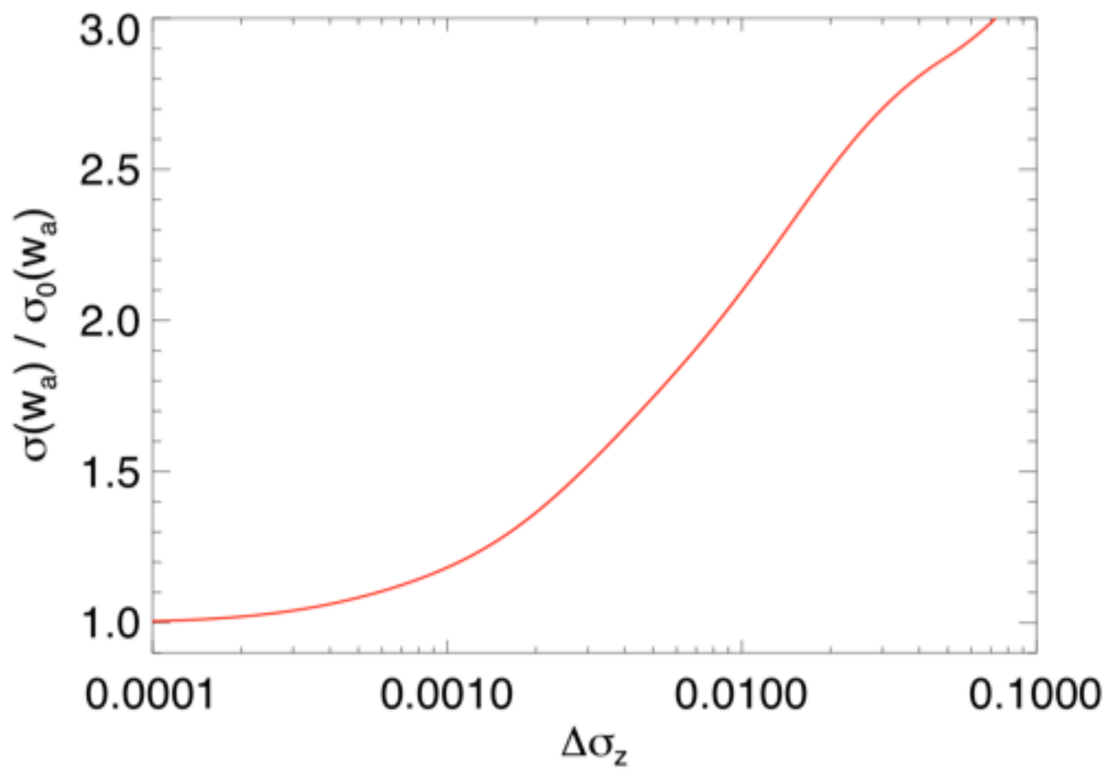


Zhan 2006

  – Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.

Two spectroscopic needs for photo-z work: training and calibration

- For weak lensing and supernovae, individual-object photo-*z*'s do not need high precision, but the calibration must be accurate - i.e., bias and errors need to be extremely well-understood

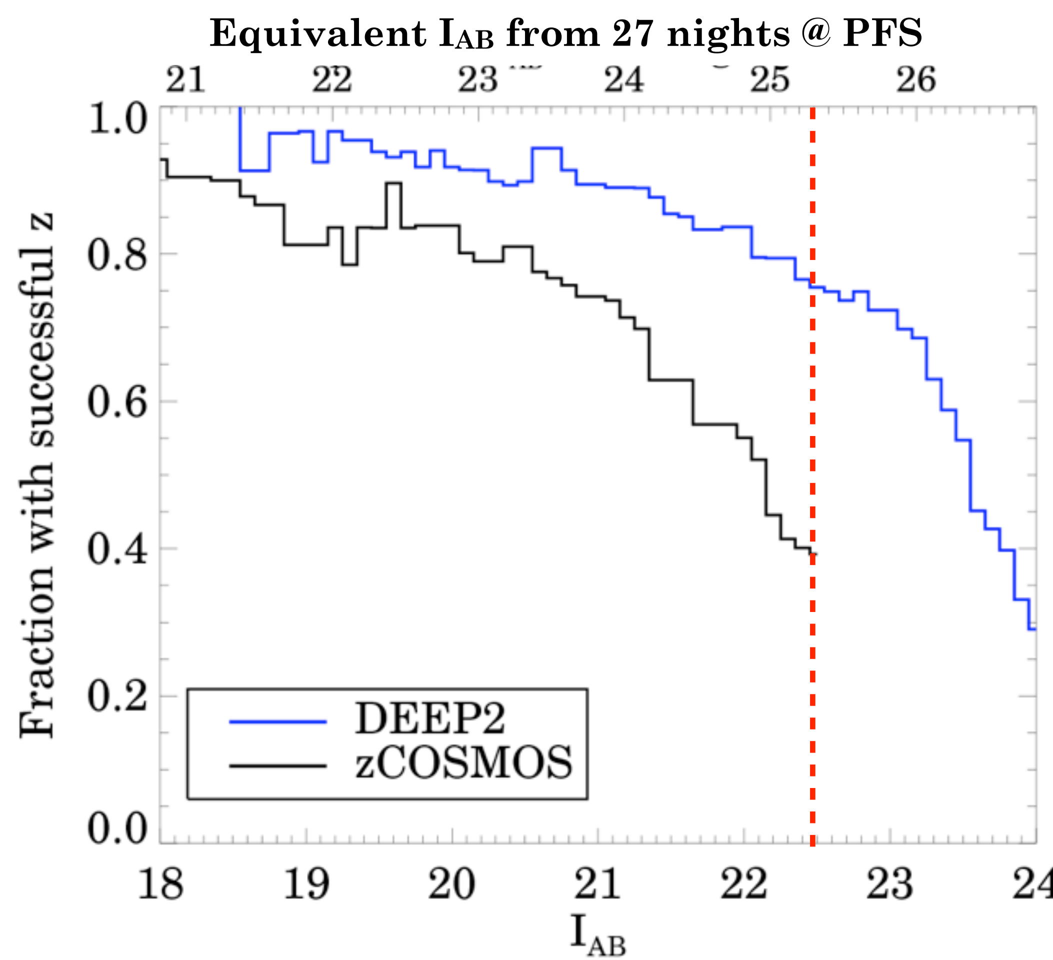


Newman et al. 2013

– *uncertainty in* bias, $\sigma(\delta_z) = \sigma(\langle z_p - z_s \rangle)$, and in scatter, $\sigma(\sigma_z) = \sigma(\mathrm{RMS}(z_p - z_s))$, must both be <~0.002(1+*z*) for Stage IV surveys

Biggest concern: incompleteness in training/calibration datasets

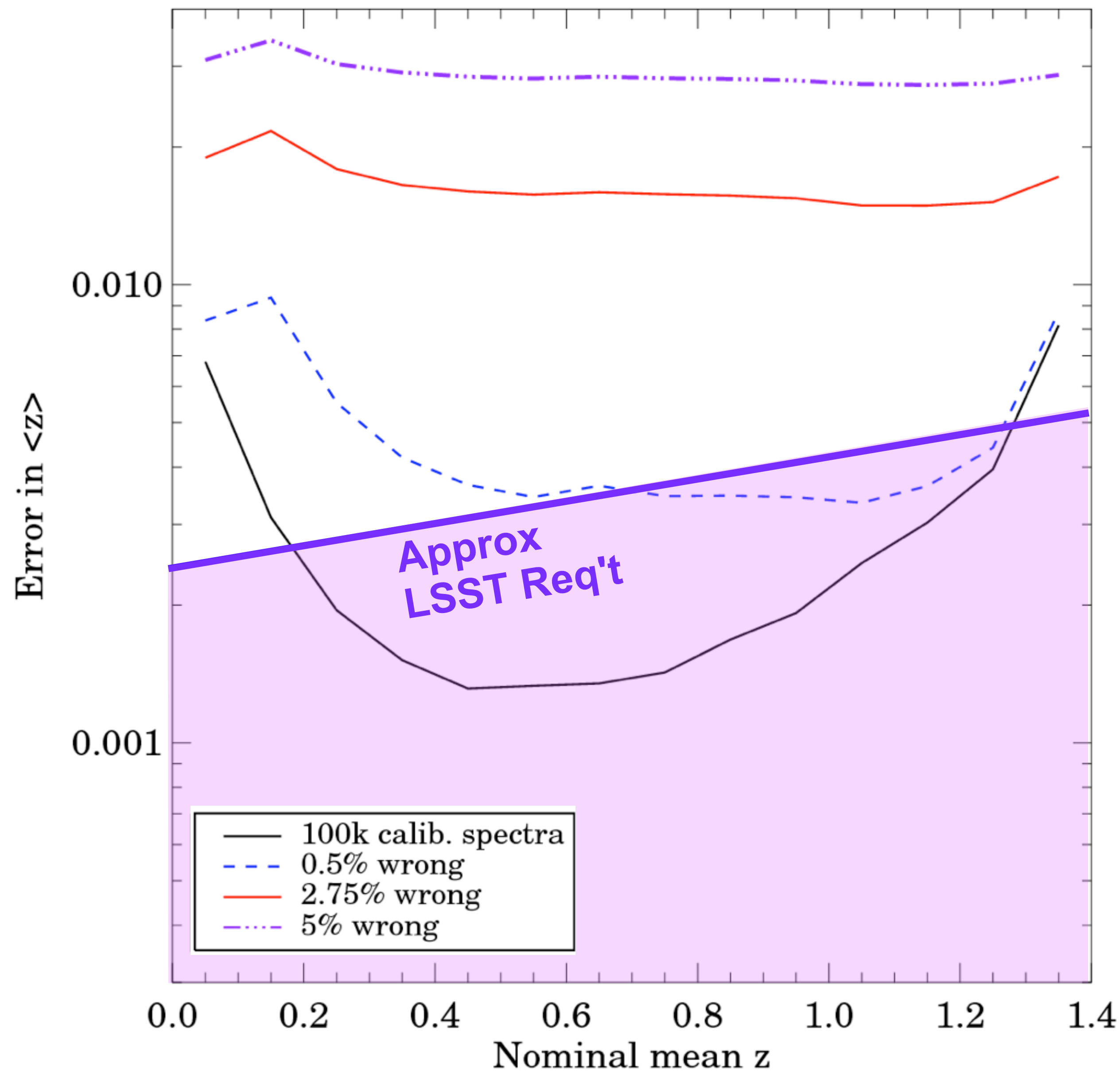
- In current deep redshift surveys (to i~22.5/R~24), 25-60% of targets fail to yield secure (>95% confidence) redshifts
- Redshift success rate depends on galaxy properties - losses are systematic, not random
- Estimated need 99-99.9% completeness to prevent systematic errors in calibration from missed populations



Data from DEEP2 (Newman et al. 2013) and zCOSMOS (Lilly et al. 2009)

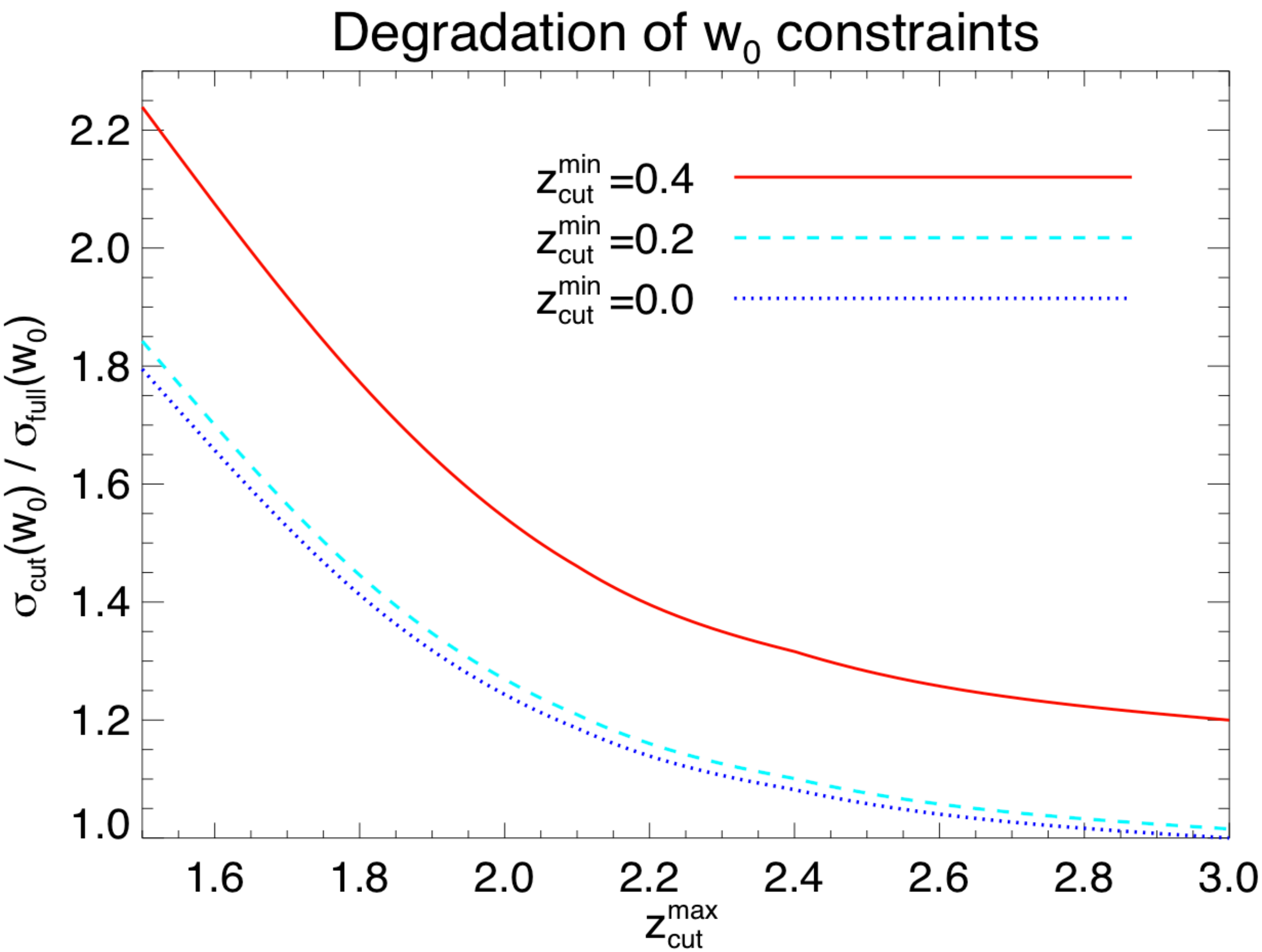
Note: even for 100% complete samples, current false-z rates can compromise calibration accuracy

- **Only the highest-confidence redshifts should be useful for precision calibration: lowers spectroscopic completeness further when restrict to only the best**



Based on simulated redshift distributions for ANNz-defined DES bins in mock catalog from Huan Lin, UCL & U Chicago, provided by Jim Annis

3 Ways to address spectroscopic incompleteness for photo-z calibration – all may be feasible



I. **Throw out objects lacking secure photo-*z* calibration**

– **ID regions in e.g. *ugrizy* space where redshift failures occurred**

– **Eliminating a fraction of sample has modest effect on FoM**

- Not yet known if sufficiently clean regions exist

3 Ways to address spectroscopic incompleteness for photo-z calibration – all may be feasible

II. **Incorporate additional information**
   - Longer exposure/wider wavelength range spectroscopy (JWST, etc.) for objects that fail to give redshifts in first try
     - Not yet known if will yield sufficient completeness
   - Develop comprehensive model of galaxy spectral evolution constrained by redshifts obtained
     - A major research program, not there now

III. **Cross-correlation techniques**

Genesis of the idea

118 *S. Phillipps and T. Shanks*

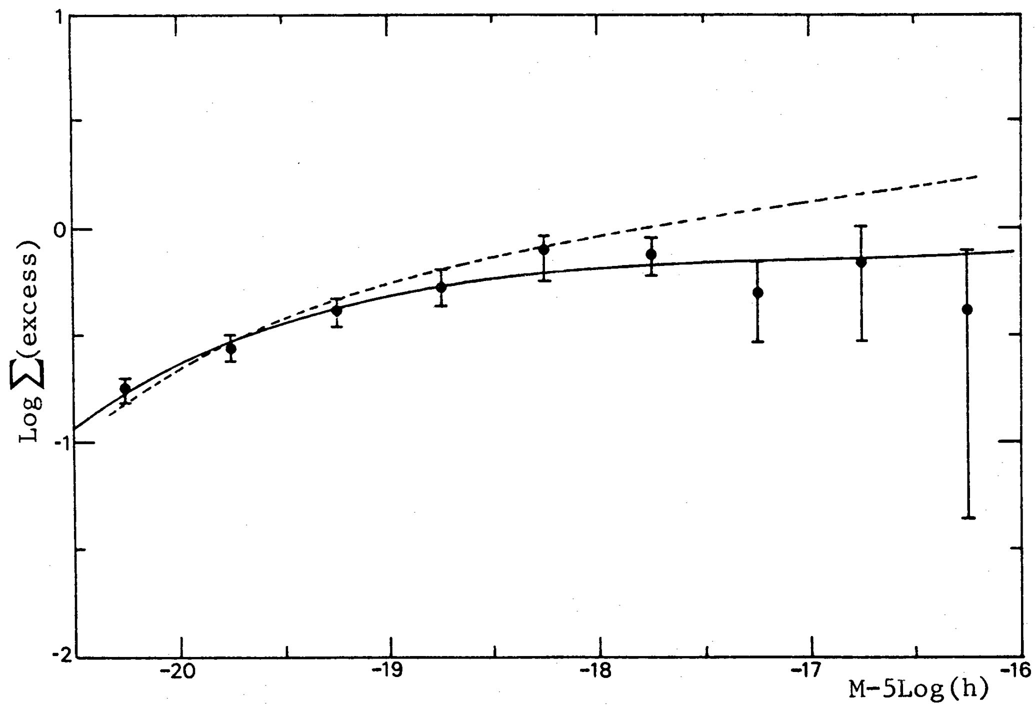
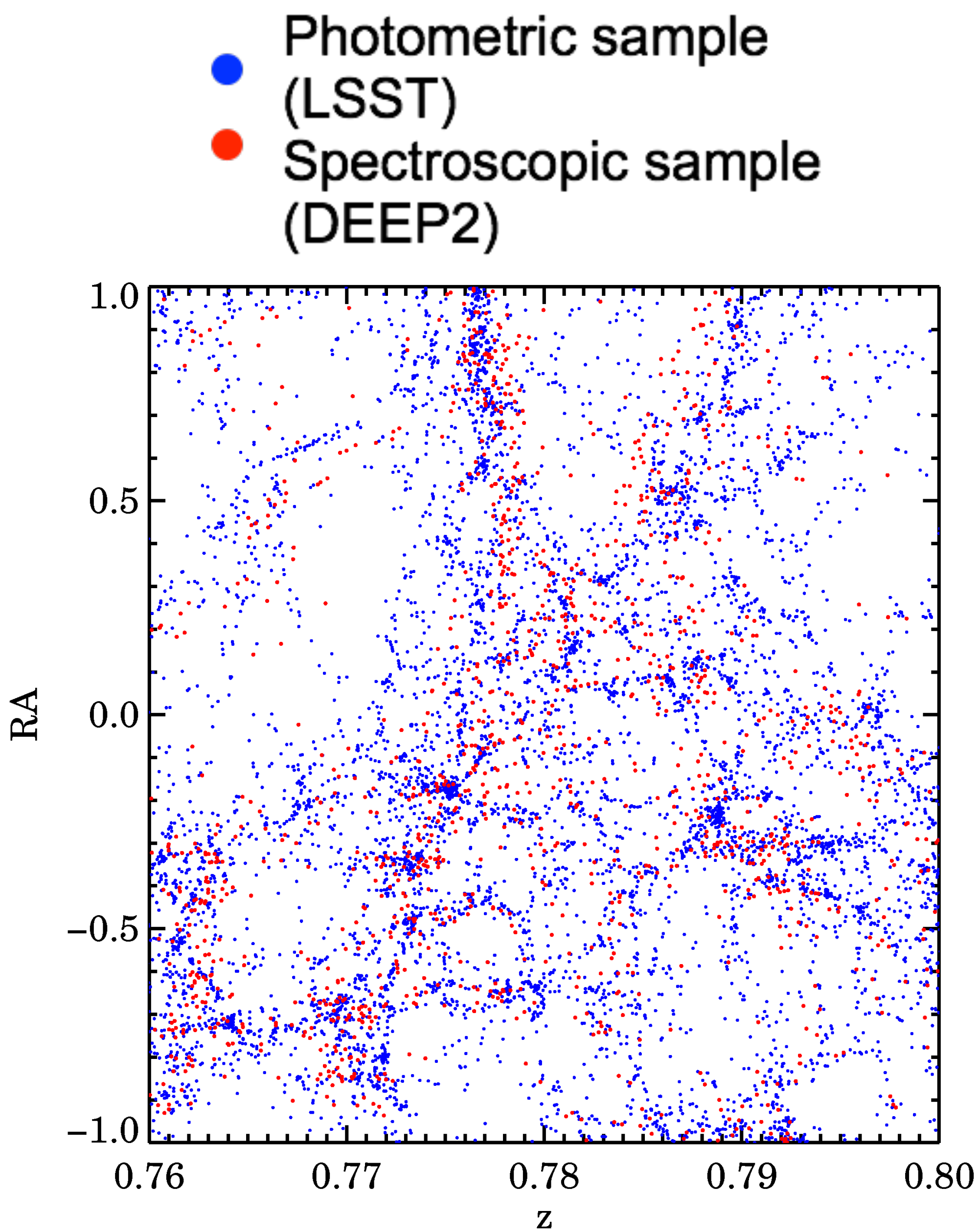


Figure 1. Variation of excess density of galaxies, Σ_{excess}, with absolute magnitude (for 0.5 mag bins). Solid (dashed) curve represents a Schechter function with slope parameter $=-1$ (-1.25) normalized to agree near $M-5$ log $h=-19.8$.

- **Phillips & Shanks 1987: Can measure luminosity function by measuring angular cross-correlation of photometric galaxies with objects of known spec-z, in bins of magnitude (260 spec-z's in ~150 sq. deg.)**
- **If you can measure luminosity function at each *z*, you can also determine the redshift distribution. . .**

Cross-correlation methods: exploiting redshift information from galaxy clustering

- **Galaxies of all types cluster together: trace same dark matter distribution**
- **Galaxies at significantly different redshifts do not cluster together**
- **From observed clustering of objects in one sample vs. another (as well as information from autocorrelations), can determine the fraction of objects in overlapping redshift range**
- **Do this as a function of spectroscopic *z* to recover *p(z)***



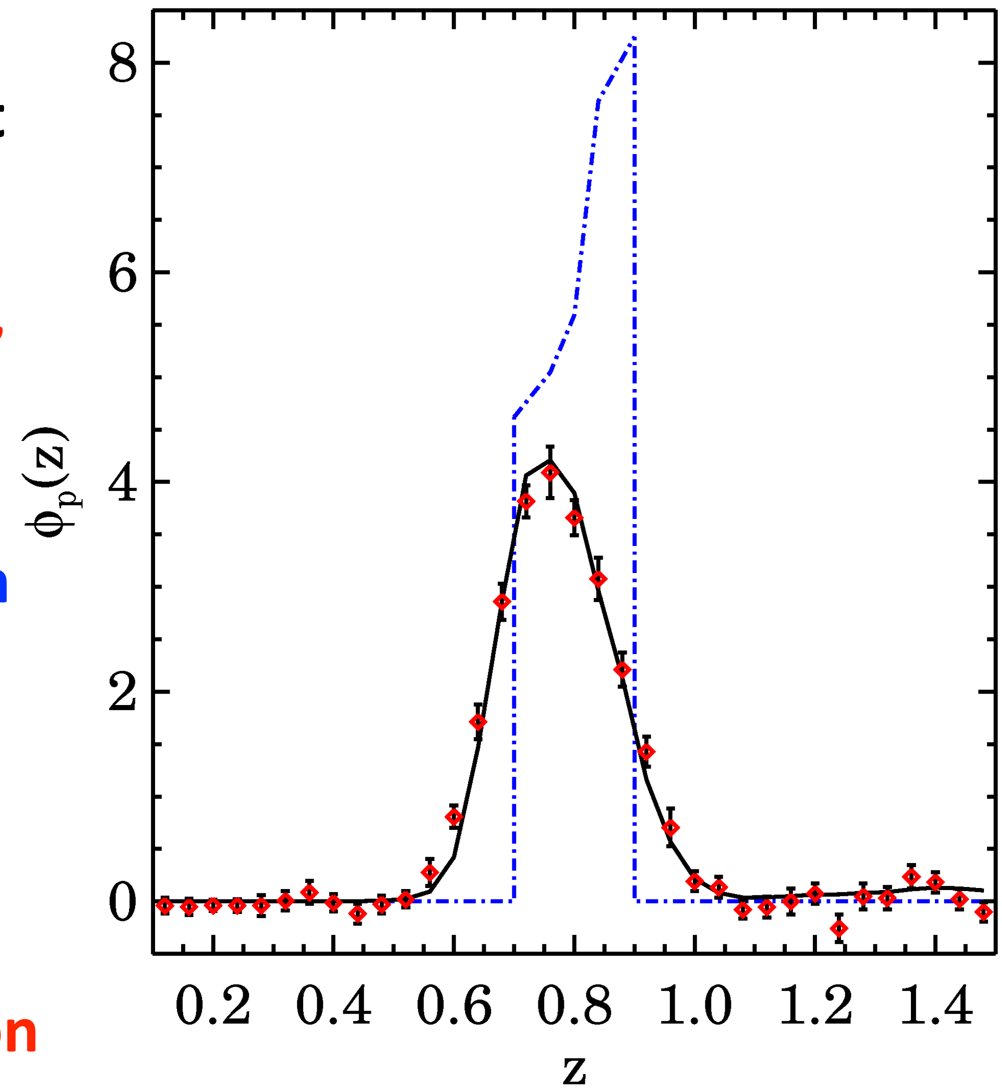
Cross-correlation methods: exploiting redshift information from galaxy clustering

- Key advantage: spectroscopic sample can be systematically incomplete and include only bright galaxies!
- See: Newman 2008, Ho et al. 2008, Matthews & Newman 2010, 2011

Blue: z_{phot} distribtion of objects with $0.7 < z_{phot} < 0.9$

Black: True z distribution of sample, spanning 24 widely-separated fields

Red: Cross-correlation reconstruction with only a R<24, 4 deg^2 survey



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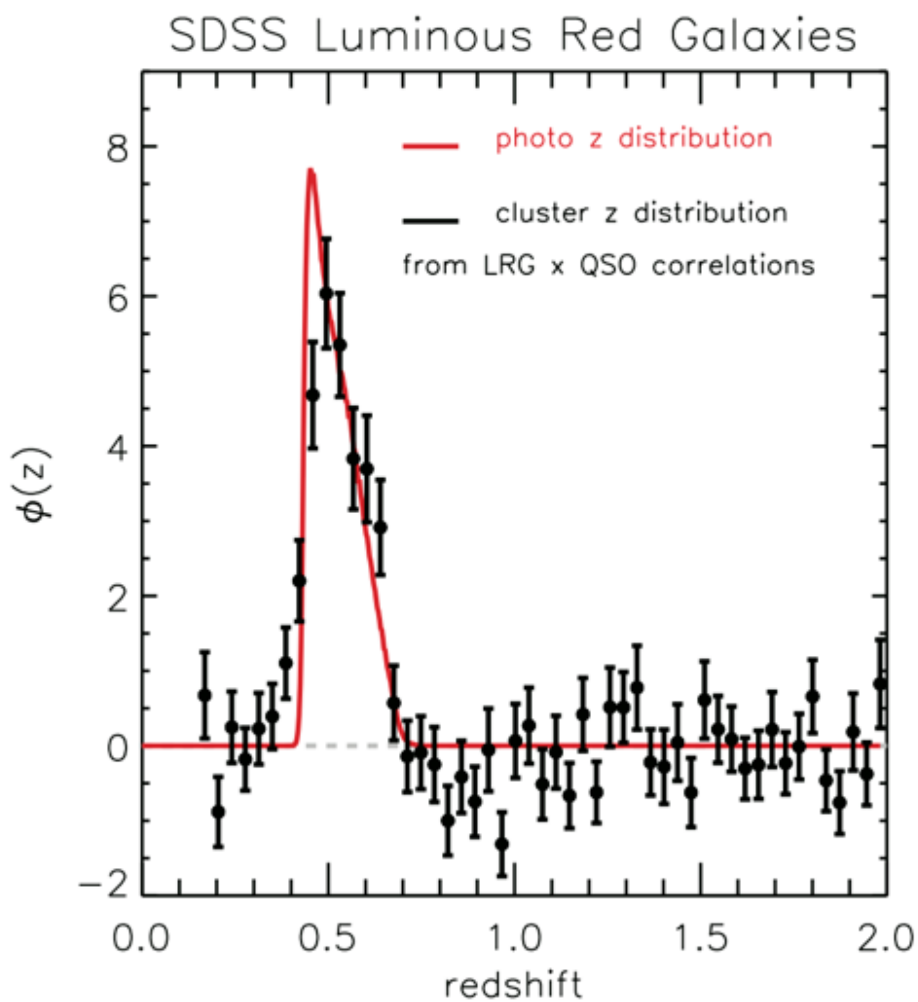
Red: Photo-z distribution for LRGs in SDSS

Black: Cross-correlation reconstruction using only SDSS QSOs (rare at low z!)



Menard et al. 2013

Cross-correlation methods: exploiting redshift information from galaxy clustering

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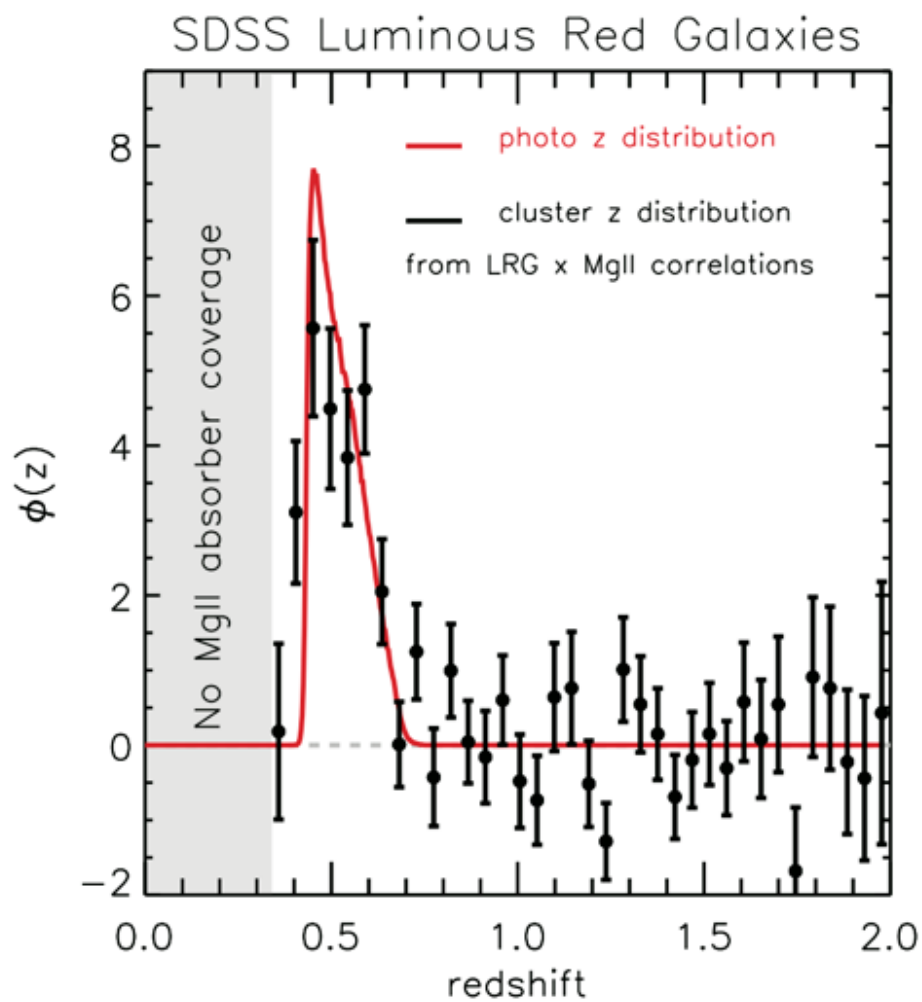
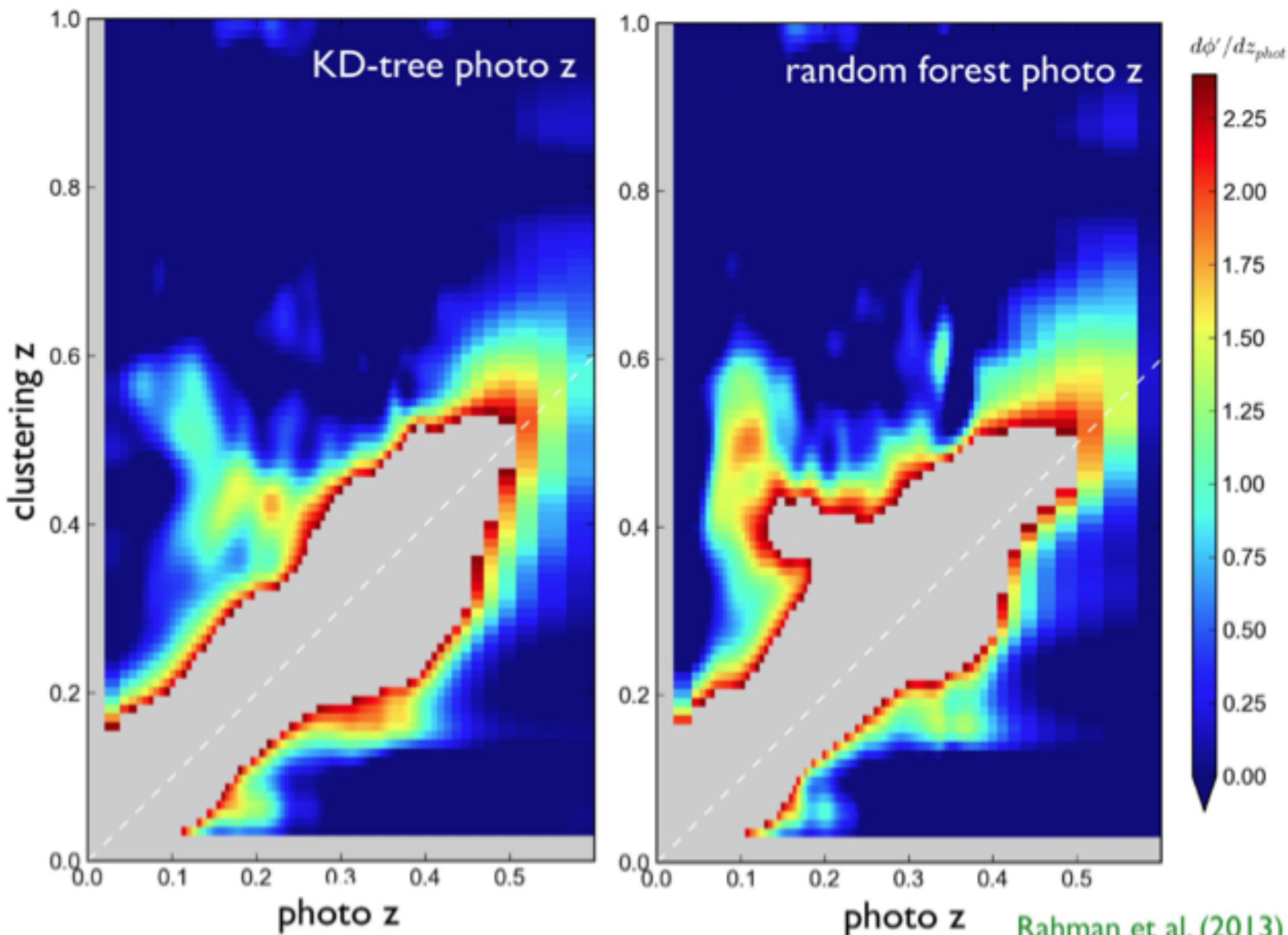
Red: Photo-z distribution for LRGs in SDSS

Black: Cross-correlation reconstruction using only SDSS Mg II absorbers (even rarer!)



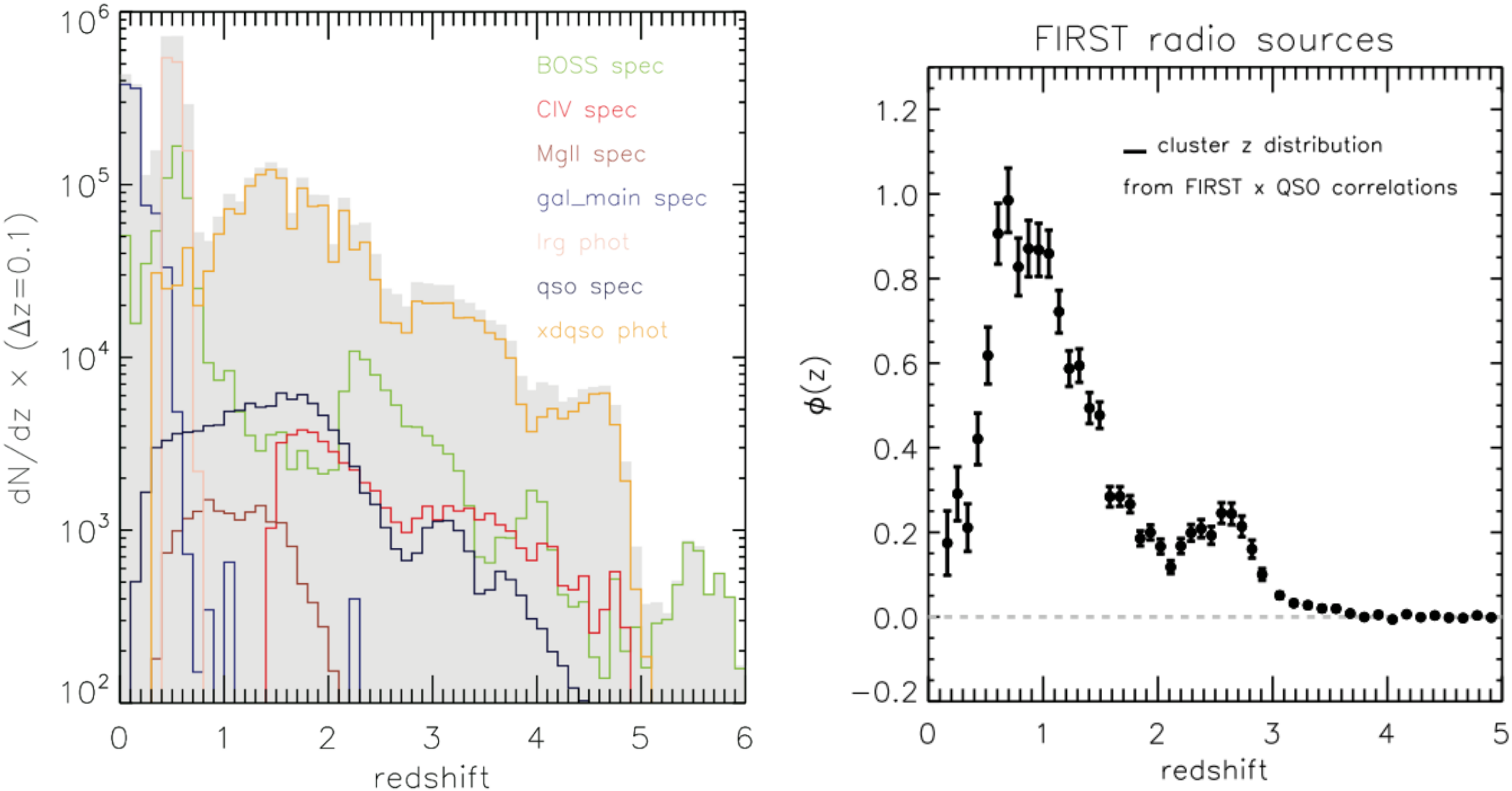
Menard et al. 2013

Cross-correlation methods have been used to test SDSS photo-z's



Rahman et al. (2013)

QSO samples are very useful at z>1: eBOSS and DESI will provide many

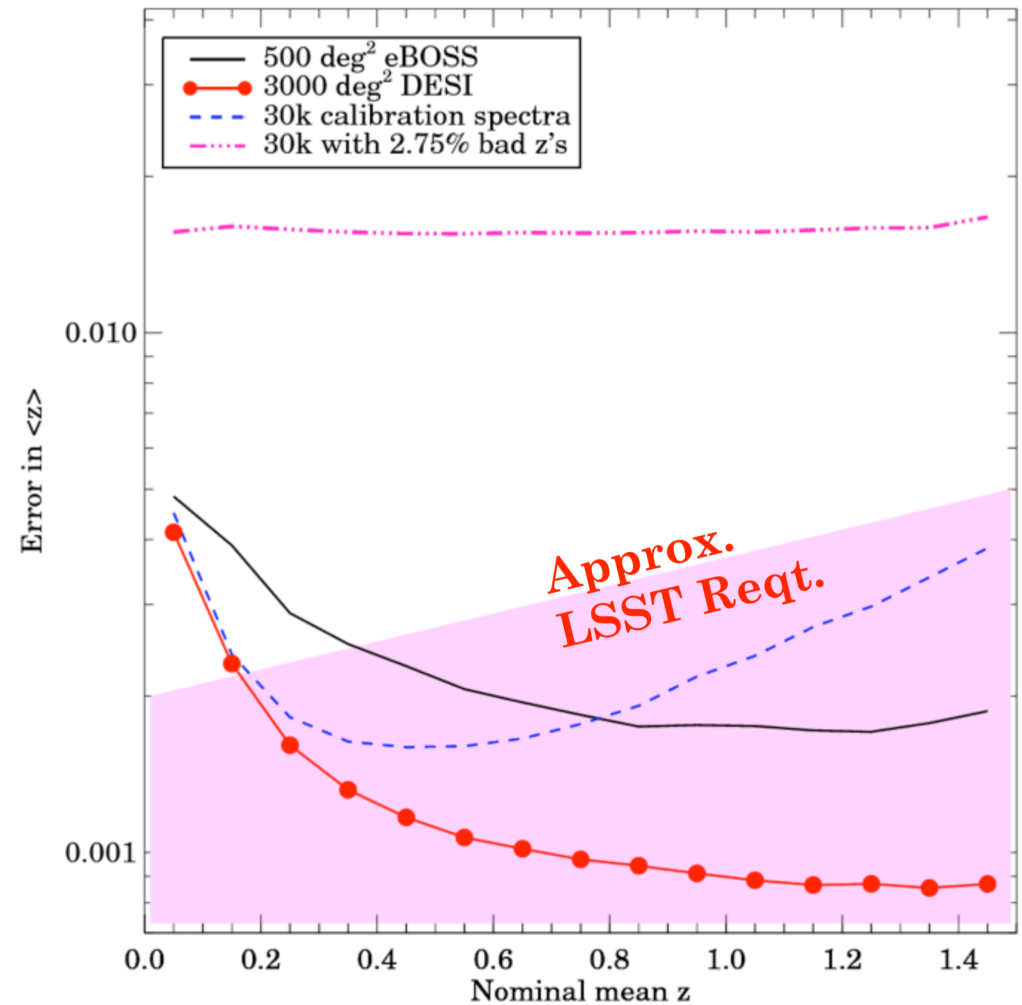


Menard et al. 2013

Cross-correlation methods can provide accurate redshift calibration for LSST

- >500 degrees of overlap with DESI-like survey would meet LSST science requirements for photo-z calibration errors to be no worse than statistical errors on weak lensing measurements

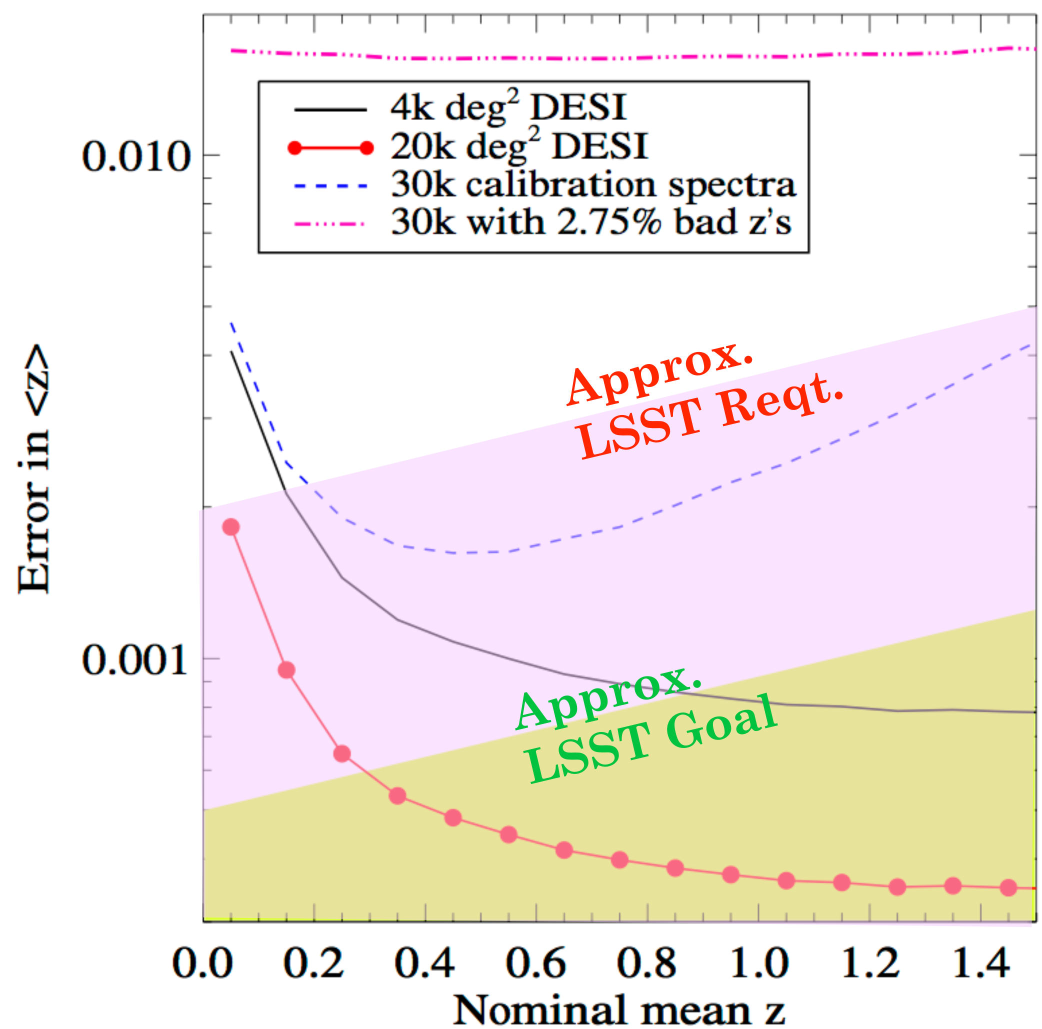
- 4000 sq. deg of overlap expected.



Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

Spectroscopic requirements for cross-correlation methods

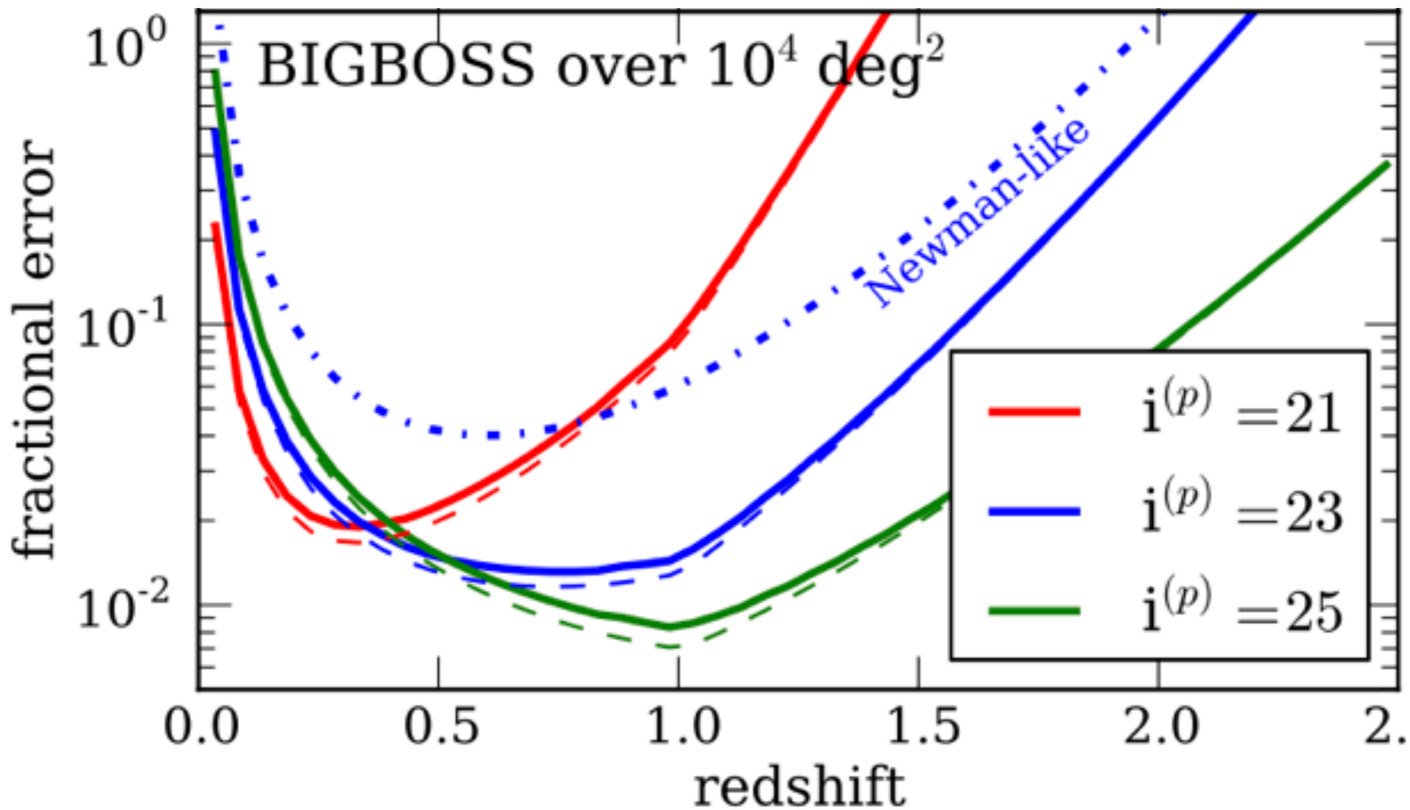
- Photo-z calibration would still be degrading Figure of Merit
- To reduce degradation to <10%, requirements are more stringent; can be met with ~20k sq. deg. overlap
- 4MOST currently plans DESI-like galaxy+QSO survey (but somewhat more dilute) in South
- DOE Cosmic Visions report recommends a wide-field Southern Spectroscopic Survey Instrument for a 4-6m telescope



Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

Those forecasts are pessimistic!

• McQuinn & White (2013): Application of optimal estimators to cross-correlation analysis

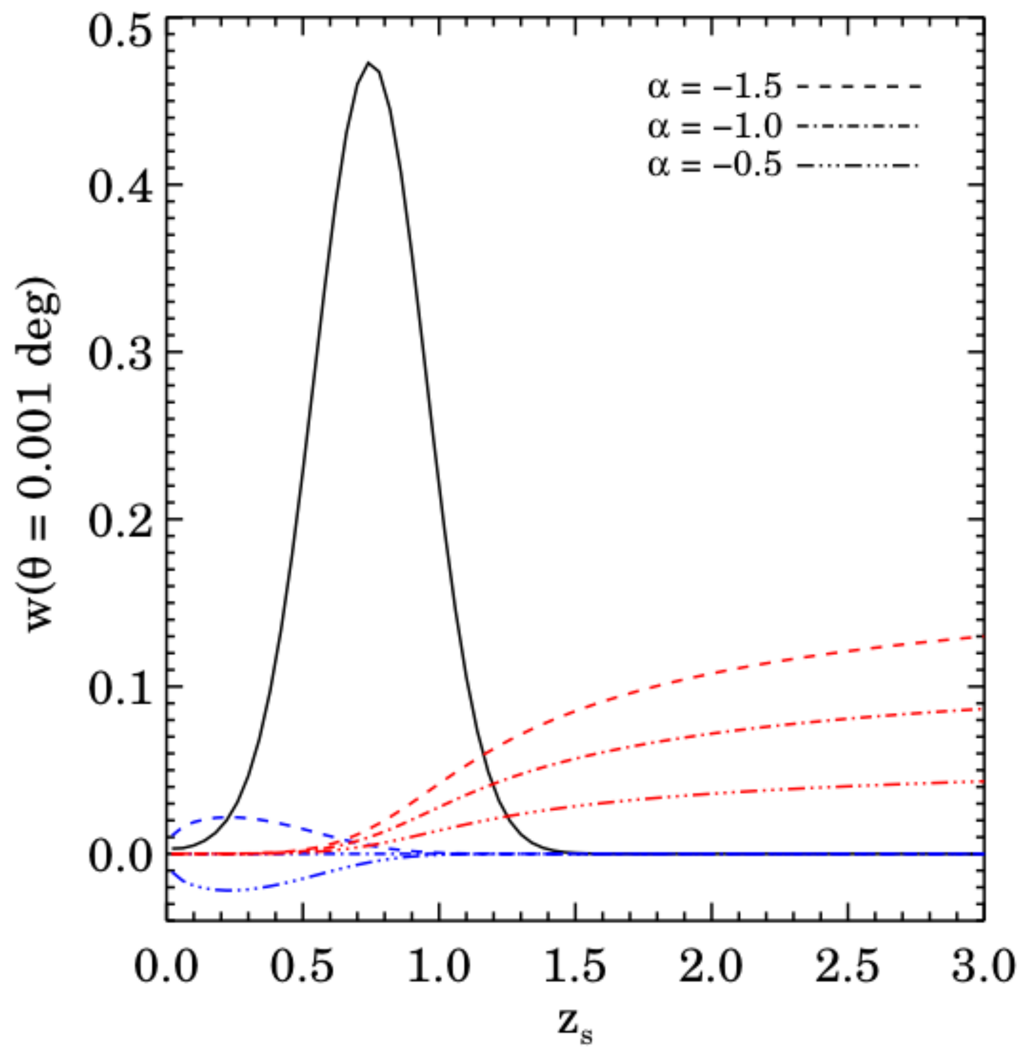


• Makes maximum use of information on linear scales, avoids integral constraint error

• Obtain errors 2-10x smaller than Newman 2008 / Matthews & Newman 2010

Biggest concern right now: disentangling cross-correlations from clustering and lensing magnification

- *Black*: cross-correlations between photo-z objects (z=0.75 Gaussian) and spectroscopic sample as a function of *z*
- *Blue*: observed cross-correlation due to spectroscopic objects lensing photometric ones
- *Red*: observed cross-correlation due to photometric objects lensing spectroscopic ones
- Weak/CMB lensing could help us predict the red curves



Matthews & Newman 2014, in prep.

Cross-correlations aren't only useful for cosmology...

- **Tal et al. 2012: cross-correlated SDSS photometric galaxies with LRGs to study the luminosity function to z=0.7**

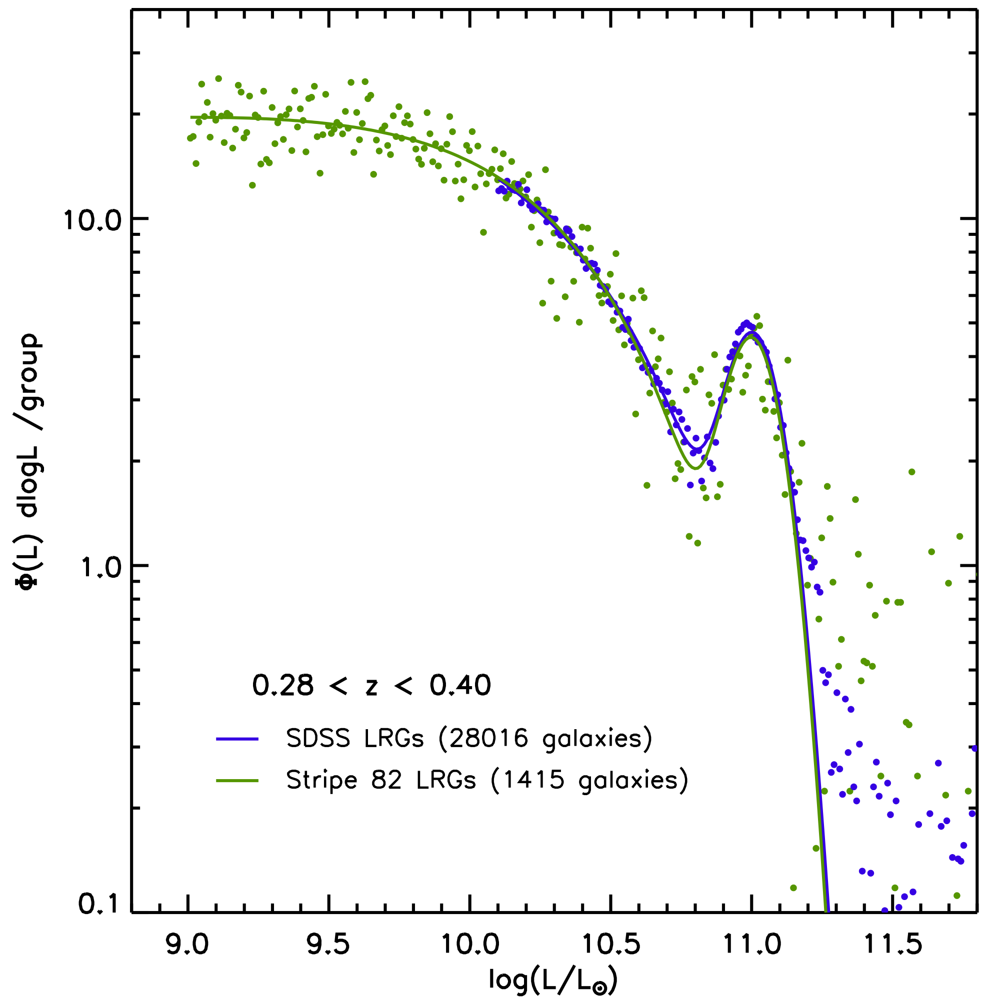
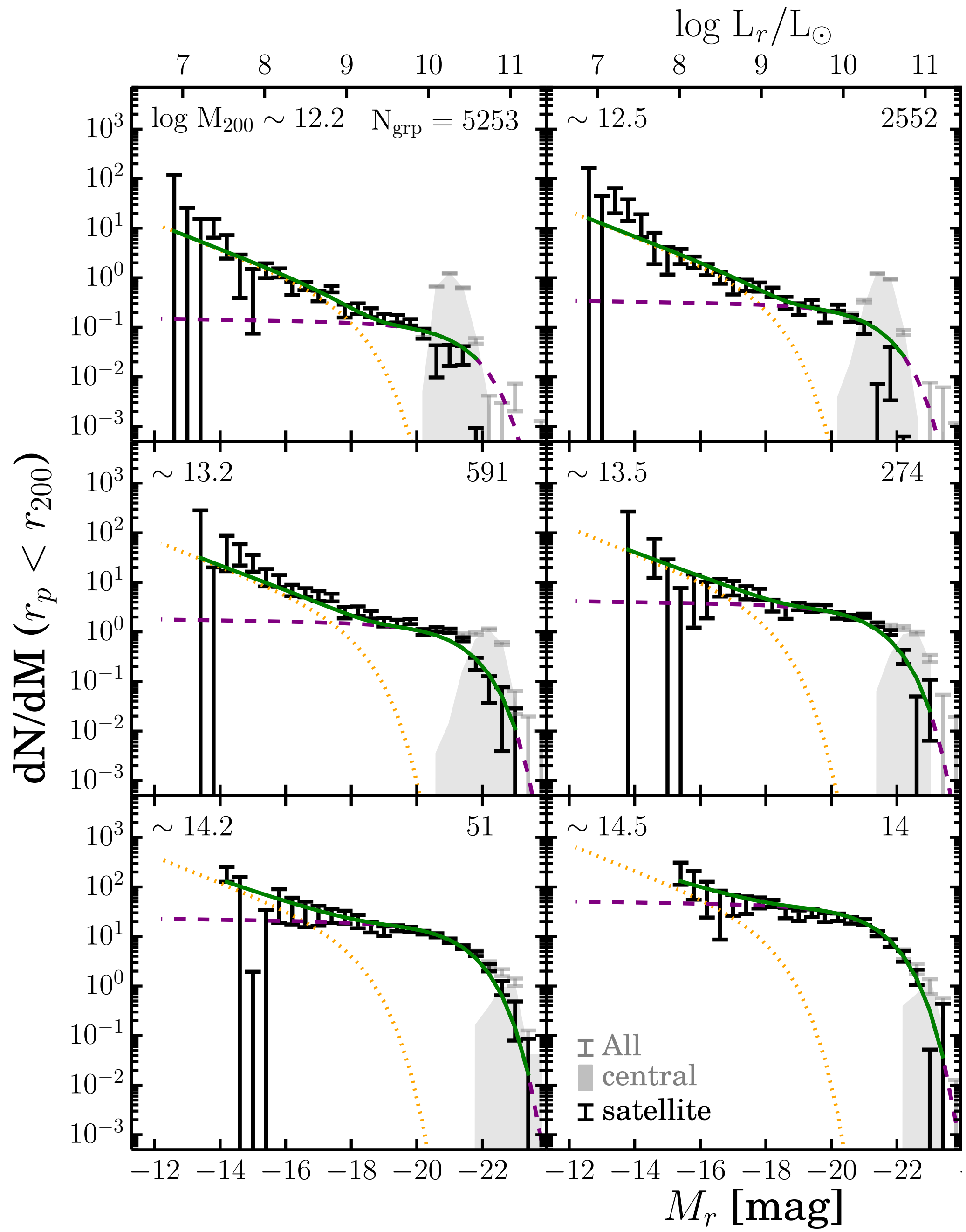


Figure 4. Comparison between the luminosity functions derived from individual SDSS LRG frames (blue data points) and from deep Stripe 82 stacks (green data points) in the redshift range $0.28 < z < 0.40$. Solid lines are functional fits to the data using the two-component model described in Section 3. The faint-end slope of the Schechter function can be reliably measured and it has a value of -0.95.

Cross-correlations aren't only useful for cosmology...

- **Ting-Wen Lan, Menard & Mo 2016: cross-correlated SDSS photometric galaxies with SDSS spectroscopic groups at 0.01 < z < 0.05 to constrain the conditional luminosity function**



Conclusions

- Photo-z's are critical for dark energy experiments
- Incompleteness or incorrect redshifts in spectroscopic samples can cause systematic errors in photo-z applications
- Cross-correlation methods can calibrate photometric redshifts even using incomplete samples of only bright galaxies & QSOs
- In addition to constraining redshift distributions, spectroscopic/ photometric cross-correlations can provide powerful probes of galaxy evolution

- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments*, http://arxiv.org/abs/1309.5384, 1309.5388

What qualities do we desire in training spectroscopy?

- Sensitive spectroscopy of ~30,000 faint objects (to *i*=25.3 for LSST)

  - Needs a combination of large aperture and long exposure times
- High multiplexing

  - Required to get large numbers of spectra
- Coverage of full ground-based spectral window

  - Ideally, from below 4000 Å to ~1.5μm
- Significant resolution (R=λ/Δλ>~4000) at red end

  - Allows secure redshifts from [OII] 3727 Å line at z>1
- Field diameters > ~20 arcmin

  - Need to span several correlation lengths for accurate clustering
- Many fields, >~15

  - To mitigate sample/cosmic variance)

Summary of (some!) potential instruments

Telescope / Instrument	Collecting Area (m^2)	Field area ($arcmin^2$)	Multiplex	Limiting factor
Keck / DEIMOS	76	54.25	150	Multiplexing
VLT / MOONS	58	500	500	Multiplexing
Subaru / PFS (≈MSE)	53	4800	2400	# of fields
Mayall 4m / DESI	11.4	25500	5000	# of fields
WHT / WEAVE (≈4MOST)	13	11300	1000	Multiplexing
GMT/MANIFEST+GMACS	368	314	420-760	Multiplexing
TMT / WFOS	655	40	100	Multiplexing
E-ELT / MOSAIC	978	39-46	160-240	Multiplexing

Table 2-1. *Characteristics of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Assuming that we wish for a survey of ~15 fields of at least 0.09 deg^2 each yielding a total of at least 30,000 spectra, we also list what the limiting factor that will determine total observation time is for each combination: the multiplexing (number of spectra observed simultaneously); the total number of fields to be surveyed; or the field of view of the selected instrument. For GMT/MANIFEST+GMACS and VLT/OPTIMOS, a number of design decisions have not yet been finalized, so a range based on scenarios currently being considered is given.*

Time required for each instrument

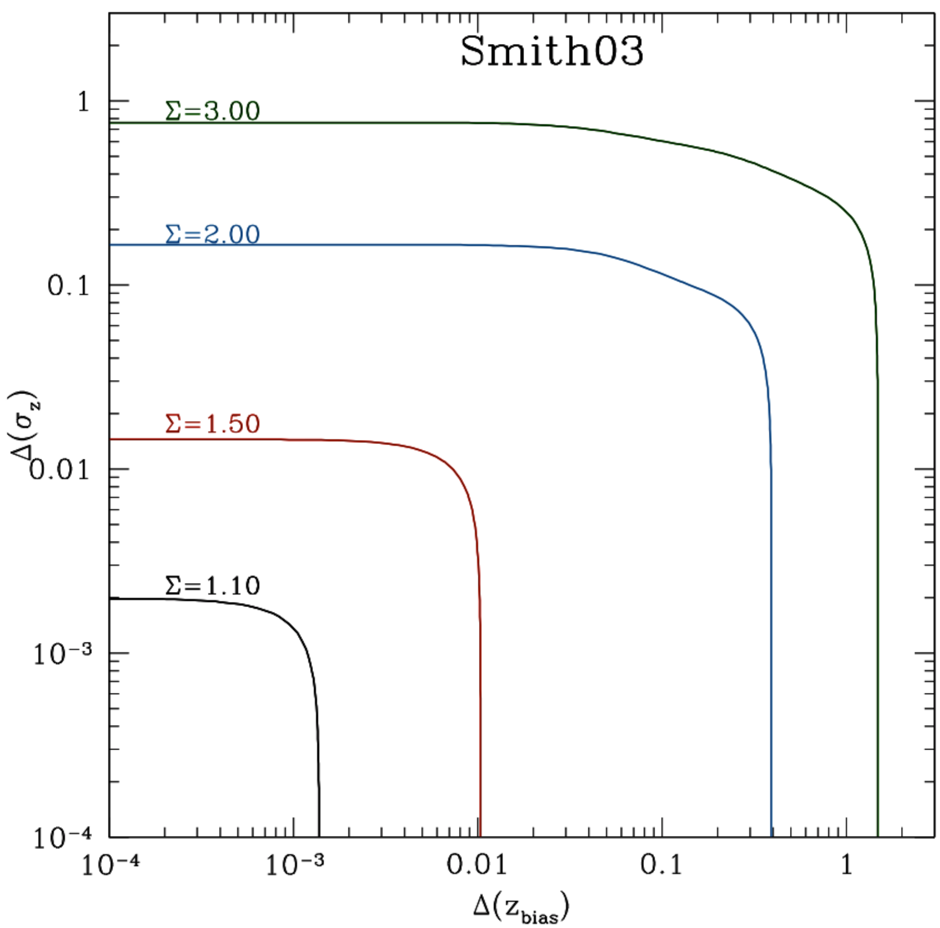
Telescope / Instrument	Total time(y), DES / 75% complete	Total time(y), LSST / 75% complete	Total time(y), DES / 90% complete	Total time(y), LSST / 90% complete
Keck / DEIMOS	0.51	10.22	3.19	63.89
VLT / MOONS	0.20	4.00	1.25	25.03
Subaru / PFS (≈MSE)	0.05	1.10	0.34	6.87
Mayall 4m / DESI	0.26	5.11	1.60	31.95
WHT / WEAVE (≈4MOST)	0.45	8.96	2.80	56.03
GMT/MANIFEST+GMACS	0.02 - 0.04	0.42 - 0.75	0.13 - 0.24	2.60 - 4.71
TMT / WFOS	0.09	1.78	0.56	11.12
E-ELT / MOSAIC	0.02 - 0.04	0.50 - 0.74	0.16 – 0.23	3.10 - 4.65

Table 2-2. *Estimates of required total survey time for a variety of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Calculations assume that we wish for a survey of ~15 fields of at least 0.09 deg^2 each, yielding a total of at least 30,000 spectra. Survey time depends on both the desired depth (i=23.7 for DES, i=25.3 for LSST) and completeness (75% and 90% are considered here). Exposure times are estimated by requiring equivalent signal-to-noise to 1-hour Keck/DEIMOS spectroscopy at i~22.5. GMT / MANIFEST + GMACS estimates assume that the full optical window may be covered simultaneously at sufficiently high spectral resolution; in some design scenarios currently being considered, that would not be the case, increasing required time accordingly.*

DE systematic errors from uncertainty in photo-z calibration

- Estimates based on Gaussian error models: photo-z bias, $\delta_z = \langle z_p - z_s \rangle$, and uncertainty in scatter, $\sigma(\sigma_z) = \sigma(\mathrm{RMS}(z_p - z_s))$, must be below ~0.003 - 0.01 for photo-z systematics to be subdominant in lensing/BAO (looser requirements come from better P(k) predictions)

- More realistic: need to consider catastrophic, non-Gaussian outliers. Can't be eliminated (e.g. HST shows 2% of faint DEEP2 objects are blends)

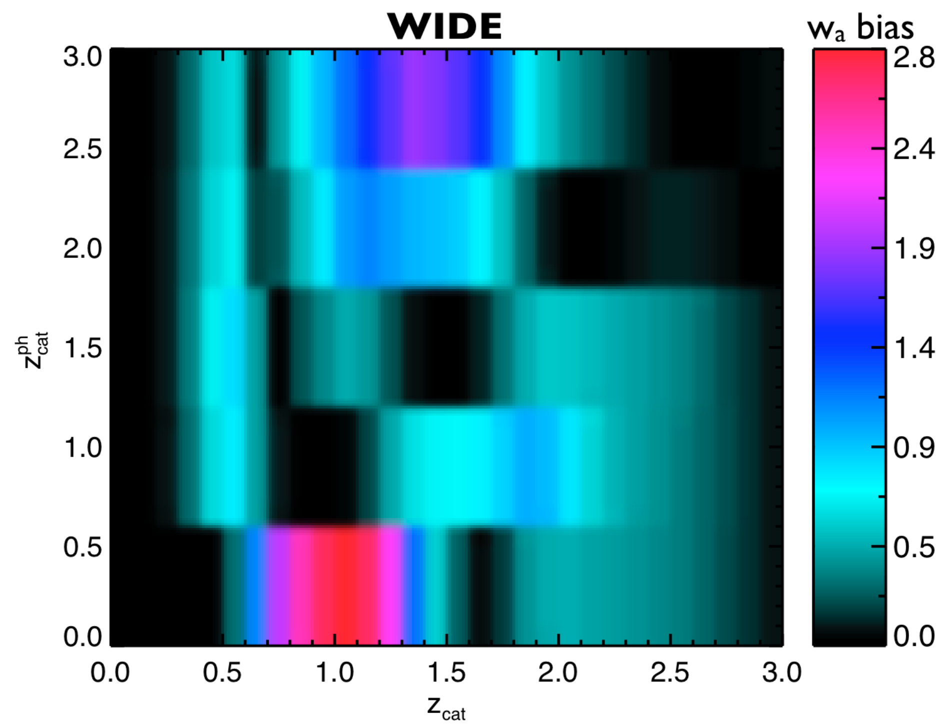


Hearin et al. 2010

- If drop all galaxies with z<0.3 or z>2.1, random lensing errors only 20% worse , but systematics much less (Hearin et al. 2010)

Systematic errors from photo-z catastrophic outliers

- More realistically: need to consider catastrophic, non-Gaussian outliers
- Can't be eliminated entirely:
  - ~2% of DEEP2 targets were actually galaxies at different *z* blurred together from ground
  - Can be difficult to distinguish one spectral break from another: degeneracies
- Some sorts of catastrophic errors worse than others
- If drop all galaxies with z<0.3 or z>2.1, lensing errors only 20% worse (Hearin et al. 2010)



Hearin et al. 2010